LLNL ON-SITE INSPECTION RESEARCH PROJECT: A PROGRESS REPORT

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ABSTRACT

We have been developing four specific technology areas that could be used during on-site inspections under a comprehensive test ban treaty: aftershock monitoring, noble gas monitoring, electromagnetic pulse monitoring, and overhead imagery detection of disturbed ground. Our investigation of aftershocks has shown that the low-frequency aftershocks that have been observed after nuclear tests at the Nevada Test Site are also associated with certain kinds of mining operations such as block caving. Our noble gas detection effort has successfully predicted the travel time of two tracer gases emplaced in the Non-Proliferation Experiment. Our EMP effort has developed a stand-off relationship for EMP sensors from the source and to date, has found that mining explosions do not generate significant low-frequency EMP. Our overhead imagery effort suggests that plant stress from shocked ground above an underground explosion may be detected using a ratio of 690 to 420 microns of visible light.

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OBJECTIVE

Under a comprehensive test ban treaty the initial detection capability for treaty violations will come from the international monitoring system (IMS). However, in many evasion scenarios—particularly those including a well-contained underground test—the IMS will not provide conclusive evidence of the nuclear nature of the event. In these cases an on-site inspection (OSI) may be necessary to gather evidence to confirm the nature of the event.

The objective of this project is to identify the phenomenology to be pursued in such inspections and to develop techniques and procedures for use during an OSI. Our project encompasses not only those techniques that would be employed after the occurrence of an ambiguous event, but also those measurements that could be employed during an on-site visit to the site of a declared explosion to confirm its nature.

Out of the many possible OSI methods, we are focusing on improving the effectiveness of a few methods which we feel are critical to the success of an OSI: aftershock characterization, noble gas seepage, low-frequency electromagnetic pulse, and the overhead detection of disturbed ground.

RESEARCH ACCOMPLISHED

Aftershocks. It is well-known that aftershocks occur after large earthquakes and that their occurrence rate decreases with time. Aftershocks from nuclear explosions behave in a similar manner but with the difference that explosion aftershock sequences include varying numbers of low-frequency events (Jarpe *et al.*, 1994; Ryall and Savage, 1969). High-frequency (*i.e.* normal aftershocks) have corner frequencies above 50 Hz, whereas low-frequency events have corner frequencies of a few Hertz. If these low-frequency aftershocks are associated only with underground explosions, then detection of such events during an OSI could help focus the efforts of the inspectors. It is important to know if these events occur in other settings.

A possible analog to rubble zone formation after an underground explosion is a block-caving mine. In this mining technique the ore body is undermined and a collapse is initiated into the mined cavity. As caving operations continue, a rubble zone is formed which extends toward the surface and may intersect it. To see if these low-frequency events are associated with block-caving operations, we deployed a microearthquake network at the Henderson mine in central Colorado, which uses block caving. Figure 1 shows a schematic cross section through the mine. Note that the rubble zone extends to the surface where it has formed a crater approximately 200 m across which is much wider than the rubble zone expected from a underground explosion of a few kilotons. Figure 2 shows an example of the waveforms from the mine compared with some waveforms from an event with similar magnitude from the nuclear test 'Hunter's Trophy' which was conducted at Rainier Mesa at the Nevada Test Site. Note that the low-

frequency events from Hunter's Trophy and Henderson are similar, especially when compared to the shot. The high-frequency content of this waveform suggests that the difference is in the source and not the structure near the station. The low-frequency events are difficult to locate because they are so emergent. Our future work will focus on developing location techniques for these events and seeing if they occur in other types of caving operations.

Noble gas seepage. A key aspect of an OSI will be to search for radioactive gases that are indicative of nuclear explosions. Of these gases, five are potential targets of collection during an OSI: Xenon-135 and -133, Argon-37, Krypton-85, and Tritium which have half lives of 9 hours, 5 days, 35 days, 11 years, and 13 years respectively. Argon-37 is the most attractive target since its half-life is long enough that it will still be detectable after several months, and has a small world-wide background. To test the transport of gas to the surface we placed bottles of two different tracer gases, Helium-3 (^3He) and sulfur hexaflouride (SF_6), in or near the explosive cavity of the Nonproliferation Experiment (NPE), an over-buried explosion in which no crater was expected to form. The bottles were crushed at the time of the explosion, releasing the gases.

The first gas to reach the surface was SF_6, in just under two months; the Helium-3 did not reach the surface until a year later. We modeled the transport of the gas to the surface with the flow and transport code NUFT (Nitao, 1993) using measured permeabilities from Rainier Mesa rocks. As an initial condition it was assumed that the gas was forced out significantly into the surrounding rock by the shock wave. We also assumed that a fracture system intersects the initial gas concentration and extends to the surface (Figure 3A). The calculation included the measured surface atmospheric pressure variations so that atmospheric pumping could be included. The model calculations are shown in Figure 3B. It qualitatively predicts the arrival of the tracer gases. If barometric pumping is left out of the calculation, many years are required to transport gas to the surface (not shown). The model also predicts that the arrival of SF_6 before the Helium-3. This difference is apparently caused by the different molecular weights of the two tracers; the heavier SF_6 causes it to have a lower gas diffusivity than the ^3He. When barometric pumping is included in the calculations as shown in Figure 3B, flow is mainly along fractures, but diffusion of gas also occurs into the porous matrix of the fracture wall. Gases with higher diffusivity (*i.e.* lower molecular weight) diffuse at a greater rate into the walls of the fracture during up flow. Thus, the higher diffusivity gas is depleted from any upward fracture flow soon after the flow is initiated. This, in turn, delays its arrival at the surface. The molecular weight of the radionuclide gas of main interest to OSI, Argon-37, is bracketed by our results and should have an intermediate arrival time to ^3He and SF_6. Our future work will include some model calculation for Argon-37 but primarily focus on collecting the 100 l samples that will be necessary for detecting Argon-37.

Electromagnetic Pulse. Underground chemical and nuclear explosions in the range of a kiloton yield or greater both generate low-frequency EMP (about 1 Hz) that are observable within several kilometers of ground zero. (Sweeney, 1989; Sweeney, 1994). These signals could be used during cooperative zerotime inspections to confirm the nature of large announced explosions. During this fiscal year we have been gathering data from explosions that LLNL is monitoring for the CTBT program to see if low-frequency EMP is observable from large ripple-fired blasts and from smaller dedicated non-nuclear explosions.

If ELF is to be useful in zerotime monitoring we need to know how far away we can expect to detect signals from an explosion of a given yield. We have assumed that the EMP signal strength falls off as the inverse cube of distance and fit the function to our data base of measured signal levels from nuclear tests to produce the plots shown in Figure 4. To date we have not observed any detectable EMP from mining explosions that we have monitored. This is probably because we cannot deploy our sensors inside the distance indicated in Figure 4.

Overhead detection of disturbed ground. Underground explosions create shock waves in the earth that can reach the surface and create strong ground motion. This motion could create effects on the surface that are observable using overhead imagery. Using the Non-Proliferation Event, we have investigated two such effects, 'fluffing' of the ground surface and plant stress. A comprehensive set of overhead imagery was taken one day before the NPE and for several days after using a low-flying airplane. Acquired imagery included 3 bands of infrared, 8 bands of visible light, and visible-light color photographs. We looked for the 'fluffing' effect by trying to identify systematic changes in surface emissivity in the infrared images—but did not find any changes associated with the NPE (Pickles, 1994).

The plant stress effect is more interesting however. Carter (1993) stressed a variety of plants in a variety of ways and looked at the plant's reflectance. He found that stressed plants show high values of the ratio of visible light of 690 microns to 420 microns. These bands are available in our imagery data and show changes that appear to be associated with the NPE. Figure 5 shows the histograms of pixel values for this ratio for before and after the NPE. Note that there is a significant increase in the ratio for data taken 56 hours after the explosion. The anomaly appears to be gone by the seventh day. Unfortunately the anomaly extends out to the edge of the imaged region, which is approximately 2 km from the NPE or approximately 0.2 G acceleration. We cannot be sure that stressed plants from the NPE are the cause of our observed data, although we did observe that at least one species of plant on Rainier Mesa underwent premature senescence a few days after the NPE. Future work will concentrate on stressing plants from ground acceleration under controlled conditions to see if this effect is reproducible.

CONCLUSIONS AND RECOMMENDATIONS

On-site inspections will be a component of any comprehensive test ban treaty that is concluded in the future. Our work will help make OSIs more effective which benefits the international monitoring regime in two primary ways: 1) an effective OSI regime will give confidence to the requesting party that a violation can be found and assures the inspected party that the inspectors will only search for relevant evidence, 2) a carefully constructed OSI capability will help keep costs to a minimum.

We plan to continue our development of the four technology areas discussed above during FY96 and to make our results available to the international community.

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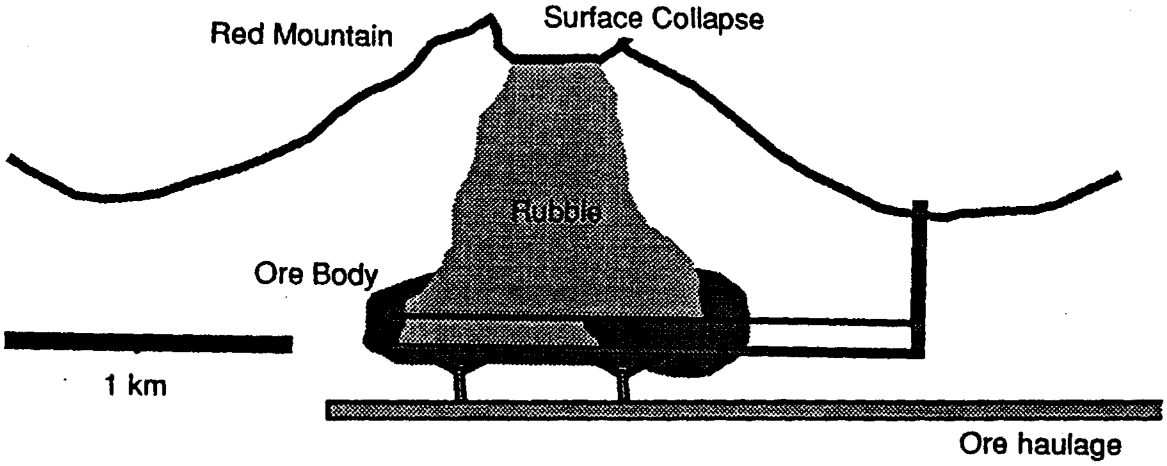

Figure 1.

Schematic cross section of Henderson mine.

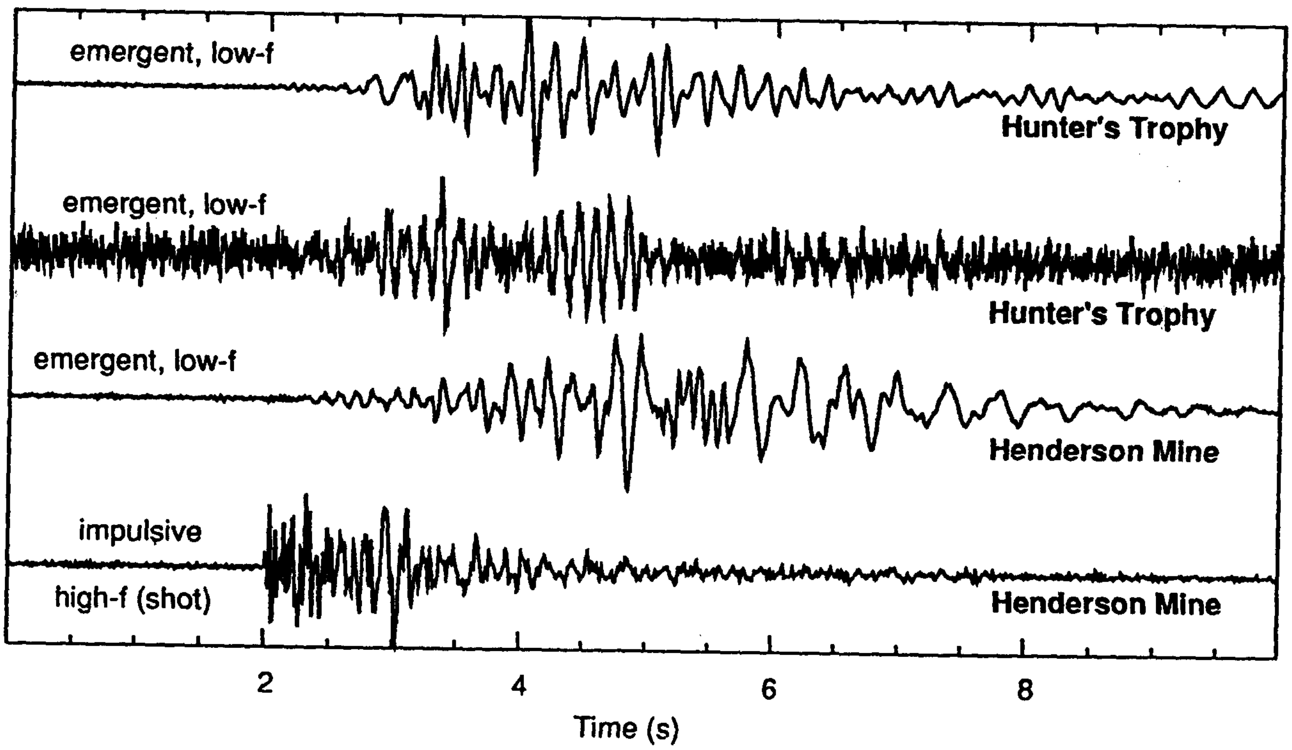

Figure 2.

Aftershocks from the Hunter's Trophy nuclear test compared to microseismic events from the Henderson mine. Hypocentral distance is 1 to 2 km from each event.

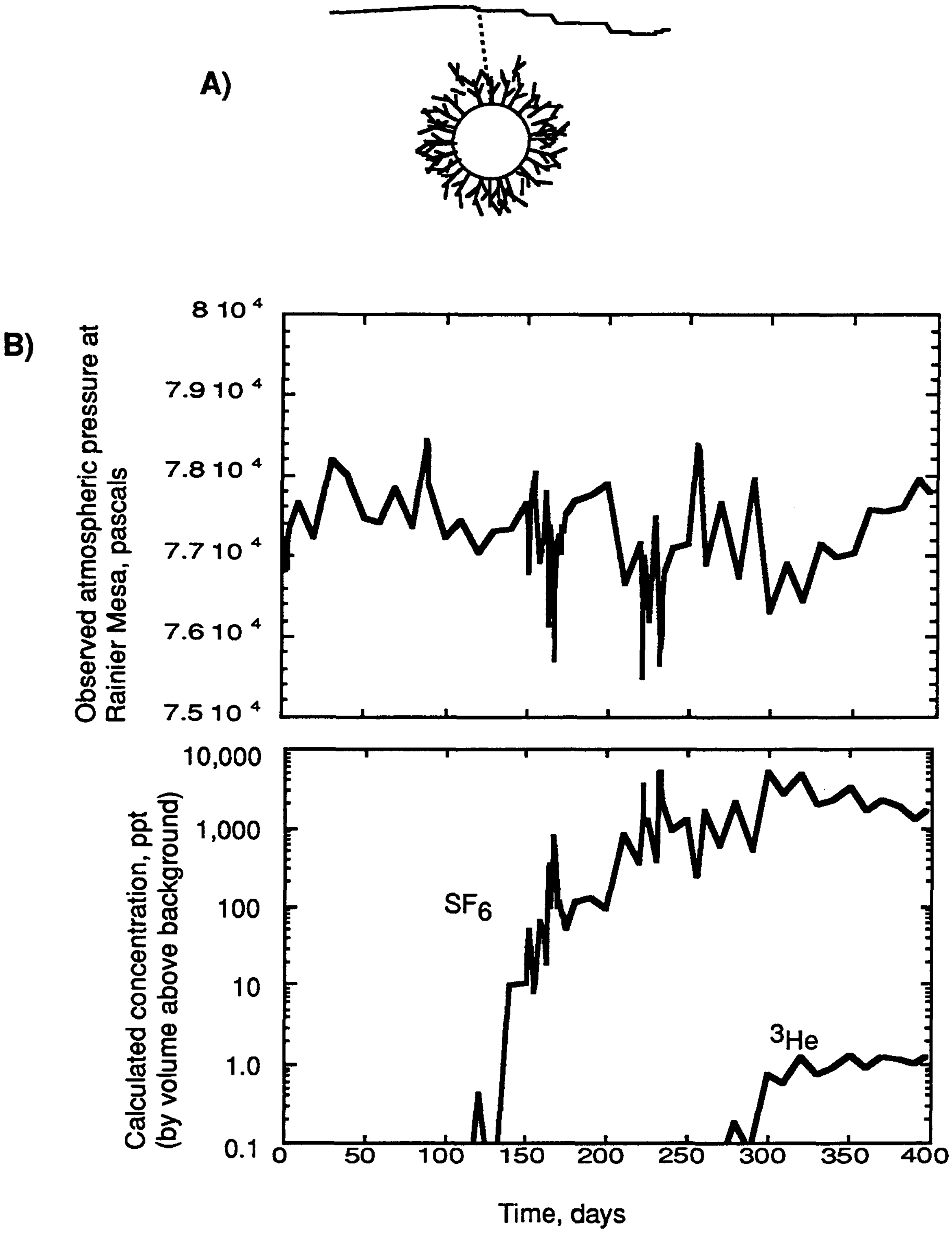

Figure 3

Gas transport model calculations. A) Schematic cross section showing the starting condition for the model. The gas has been forced out into the rock along fractures from the explosion. B) Results of the calculation. The upper panel shows the observed pressure at Rainier Mesa. Gas was released at zero time.

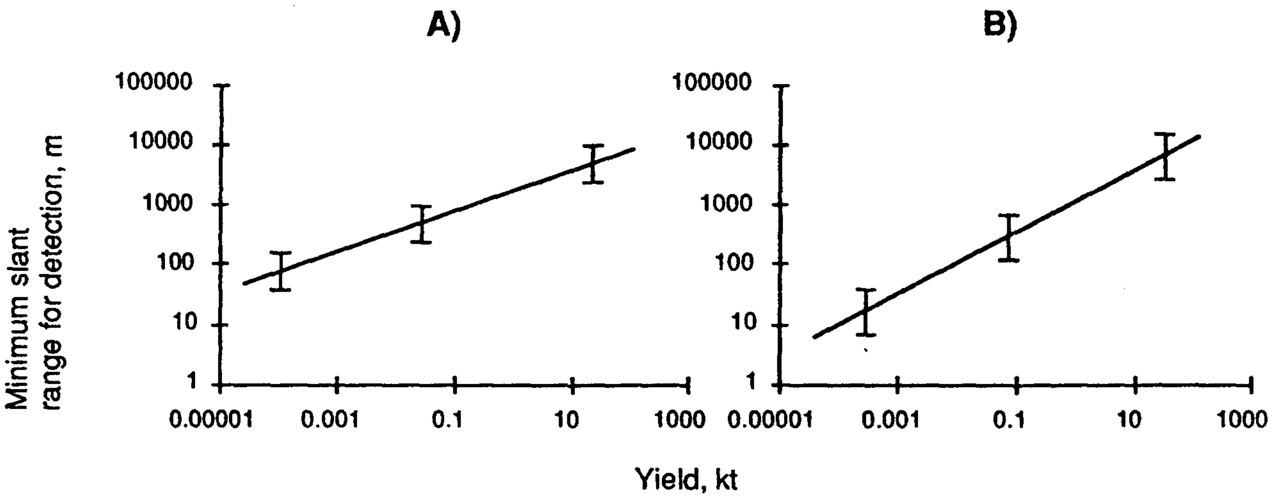

Figure 4.

Calculated minimum slant range standoff distance for detection of electromagnetic pulse from underground explosions: A) Magnetic, B) Electric. In each case the line represents the best fit to the empirical data, the bars indicate uncertainty.

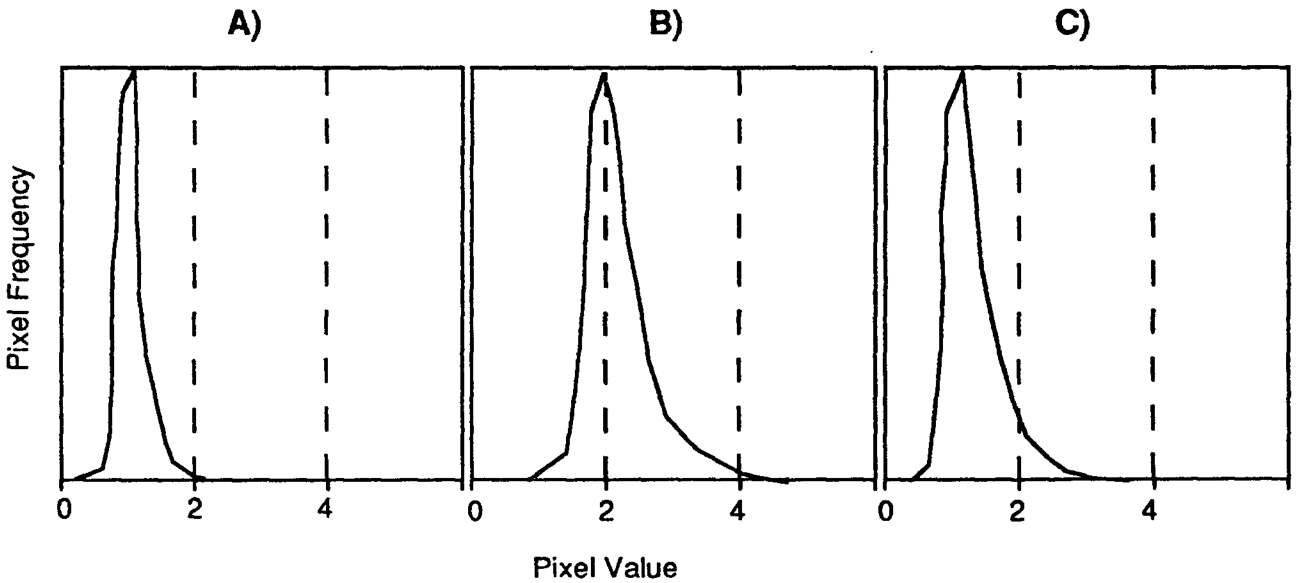

Figure 5.

Histograms of pixel values for the visible light ratio of 690 to 420 microns.
A) Before the NPE. B) 56 hours after C) 7 days after.